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FULL LENGTH ARTICLE

Oceanography of the Gulf of Aden John Murray–Mabahiss Expedition 1933–1934 Revisited

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Abstract Oceanography of the Gulf of Aden was the focus of several recent publications using STD casts, XBT and AXBT. The present paper is based on the unpublished data set of John Murray–Mabahiss Expedition to the Indian Ocean 1933–1934. In addition to its historical value, these bottle data have an exceptional significance. Unlike most cruises, the data were collected in two successive monsoon seasons and in cross sections between the African and Arabian coasts of the Gulf, in addition to the longitudinal section along the ship's transit. This gave a rare glimpse of what the density and oxygen were in 1933/34. The paper describes the water masses and circulation in the southern Red Sea and Gulf of Aden before the Second World War, or in other words, the state of the art at that era, when oceanographic data were very scarce. The study reveals pronounced spatial and seasonal variability in the hydrographic structure and circulation pattern in late summer and winter monsoons. Upwelling and frontal zones, which are known to be characterized by a high biological productivity, are developed during the summer season. The deep high saline outflow from the Red Sea into the Gulf of Aden is stronger in winter.

Several water masses are identified as: the Surface Water Mass (SW) of high salinity, the Gulf of Aden Subsurface Water Mass (GASSW) of intermediate minimum salinity, the Red Sea Water Mass (RSW) of intermediate maximum salinity, the Persian Gulf Water Mass (PGW) and the Deep Water Mass (DW). The Gulf of Aden subsurface water mass (GASSW) is poor in oxygen (<0.5 ml l^{-1}). This subsurface water of anoxic oxygen concentration occurs at shallower depths (<20 m) in summer, particularly in the upwelling regions. The deoxygenating process and its impact on the ecosystem and communities, as well as the oceanic variability, are key elements in managing the living resources of the region.

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The conclusions reached from this work are in general agreement with those obtained from the more recent studies. The broad features of the oceanography of the region could have been made available to oceanographers 80 years ago, if the data and results of John Murray–Mabahiss Expedition (JMME) had been timely published following the return of the expedition.

Introduction

The Gulf of Aden (Fig. 1a) is connected at its northwesterly extremity to the Red Sea through the Strait of Bab El Mandab and is opened at its easterly end to the Arabian Sea through a wider and deeper mouth. The actual separation between the Gulf of Aden and the Red Sea lies at the sill near Great Hanish Island (≈150 km NW of Bab El Mandab) where depths are of the order 50 m except for a 6 km wide trench 160 m deep at mid channel (Murray and Johns, 1997)

The climate of the Gulf of Aden is dominated by hot and extremely arid conditions. The area is subjected to reversing monsoons. During the NE monsoon (October to May) the prevailing wind over the Arabian Sea is northeasterly veering to easterly in the Gulf of Aden and southeasterly towards the Strait of Bab El Mandab and Southern Red Sea. The stronger winds during the SW monsoon (June–September) are from WSW over the Gulf of Aden and Arabian Sea and from NW over the Southern Red Sea.

According to published literature including direct observations and modeling, the monsoonal reversal of winds coupled with the thermohaline circulation result in changes in circulation in the Strait of Bab El Mandab and Gulf of Aden. In Bab El Mandab, during the winter monsoon, there are two layers system, while during summer there are three layers system of water exchange between the Red Sea and the Gulf of Aden (Thompson, 1939b; Siedler, 1968; Morcos, 1970; Patzert, 1974; Poisson et al., 1984; Murray and Johns, 1997; Sofianos et al. 2002; Sofianos and Johns, 2002). The subsurface warm and high saline outflow from the Red Sea into the Gulf of Aden is distinctly seasonal. It increases during winter (October to May) and attenuated or blocked in summer (July–August) (Seriy, 1968; Patzert, 1974; Osman, 1985; Maillard and Soliman, 1986; Murray and Johns, 1997; Bower et al., 2000; Beal et al., 2000; Peters et al., 2005). In a study of the Red Sea budget of salinity, Souvermezoglou et al. (1989) found a gain for the Red Sea in summer, and a loss in winter. In the Gulf of Aden, the winter northeasterly winds cause surface water to

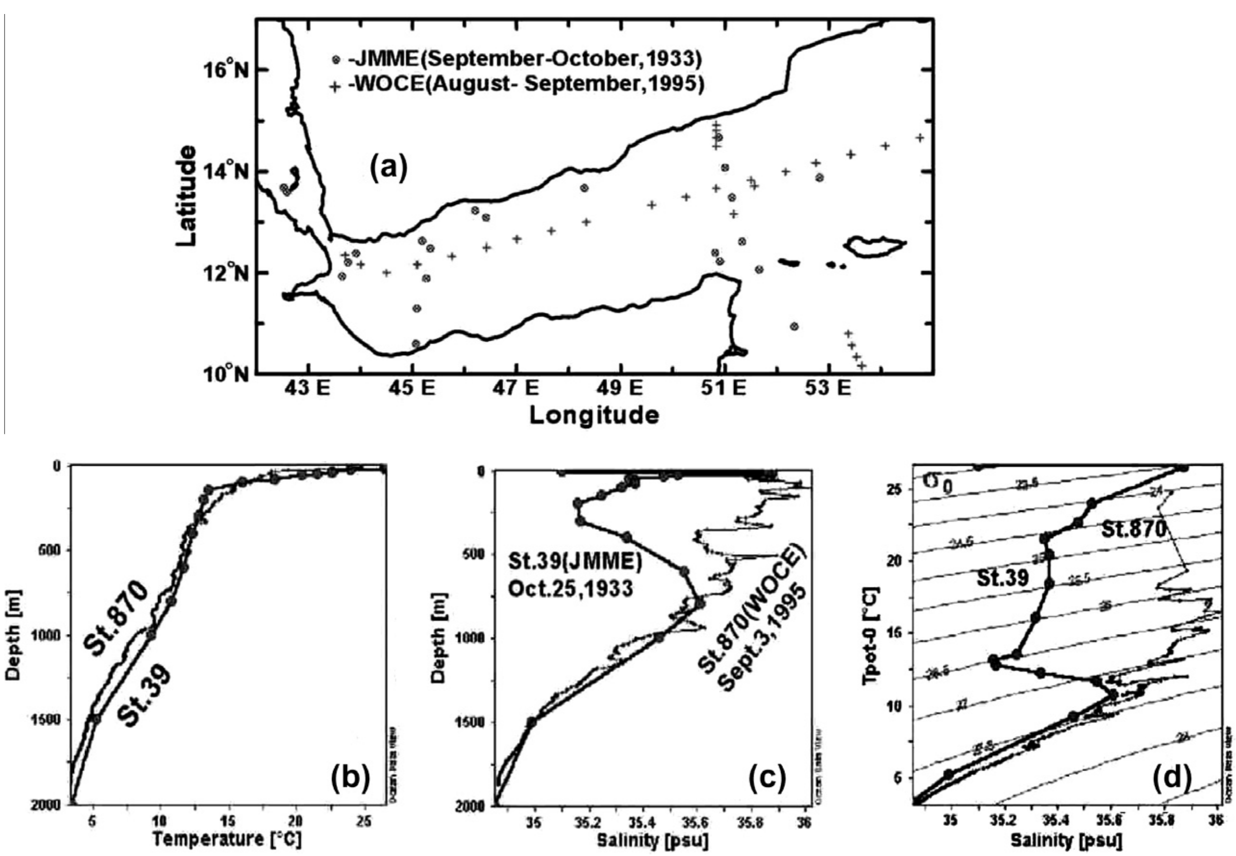


Figure 1 John Murray/Mabahiss Expedition (Station 39: 13°53′N, 52°54′E) compared to recent observations of Knorr (Station 870: 14°09.67′N, 52°46.33′E), (a) Location of stations in Gulf of Aden in summer: • JMME/Mabahiss, September–October, 1933, + WOCE/Knorr, August–September, 1995, (b) Temperature profile, (c) Salinity profile, (d) Temperature–salinity diagram.

move towards Bab El Mandab, particularly against the Arabian coast. Along the African coast there is a weak current in the opposite direction and a cyclonic eddy in the central part of the Gulf of Aden (Seriy, 1968). During the summer season, the stronger winds of the SW monsoon cause the surface water to move out of the Gulf of Aden towards the Arabian Sea and an anticyclonic gyre is developed in the central part of the Gulf of Aden (Stirn et al., 1985). The strong winds of the SW monsoon during July–September also cause an intensive seasonal upwelling over a very wide area off Southern Arabia (Bogdanova, 1966; Smith, 1968; Swallow, 1984; Stirn et al., 1985; AbdAllah, 2001). More recently Bower et al. (2002) observed large, energetic, deep-reaching mesoscale eddies that fundamentally influence the spreading and pathways of intermediate Red Sea water.

The John Murray–Expedition to the Indian Ocean on the Egyptian research vessel Mabahiss 1933/1934 (JMME) covered five regions: the Red Sea, Bab El Mandab Strait, Gulf of Aden, Arabian Sea and Gulf of Oman. The hydrographer of the expedition E.F. Thompson published his studies on the Red Sea and the exchange over Bab El Mandab sill (Thompson, 1939a,b). While his contributions were cited by Sverdrup et al. (1942) and became standard references in oceanography for many years, his studies of the Gulf of Aden, Arabian Sea, and Gulf Oman remained virtually unknown in his unpublished dissertation in the University of Cambridge (Thompson, 1936). Fifty years later, a copy of Thompson dissertation was released by the University of Cambridge to the first author (S. Morcos). The purpose of the present paper is to bring this case to the attention of today's oceanographers and to establish the state of the art of oceanographic research at the time of JMME. The Expedition was the largest and most detailed survey before the International Indian Ocean Expedition (IIOE). With the decline of oceanographic surveys during world war II, the observations of JMME became the only data set bridging a gap of three decades between the limited observations of Snellius (1929) and Dana (1929–1930) and the beginning of IIOE in the early 1960's. The authors are encouraged by the recognition of the value of the historical data as manifested by "The Global Ocean Data Archaeology and Rescue Project (GODAR)" launched by IOC and its member states in 1993. The project seeks out and recovers manuscripts and digital oceanographic data not yet included in the accessible digital oceanographic data bases of the data centres.

Most of the oceanographic research in the Gulf of Aden, was made by ships in transit between the Red Sea and Indian Ocean. John Murray/Mabahiss Expedition was the first to occupy three cross sections in the Gulf in addition to the "traditional" section along the axis of the Gulf and in two successive monsoon seasons (summer 1933 and winter 1934). In their study of three-dimensional circulation in the Red Sea, Sofianos and Johns (2002,2003), noted that handful of expeditions followed the central axis of the Red Sea. As a result, most of the descriptive and theoretical investigations of the Red Sea circulation follow a two-dimensional approach (in the latitude–depth plane). In fact, JMME gave special attention to the Gulf of Aden leaving the detailed investigation of the Red Sea to the Egyptian Expedition to the Red Sea, that followed one year later. Mabahiss occupied five sections across the Red Sea and investigated the Gulf of Aqaba in winter 1934/35 (Mohamed, 1940; Morcos, 1970; Morcos and Soliman, 1974).

In the Gulf of Aden, many of the observations made in the sixties during the IIOE were not far from the main track of JMME 1933/34 (e.g. Khmitsa, 1968; Seriy, 1968; Siedler, 1968). Few of these efforts were devoted to study the inner part of the Gulf of Aden or to repeat their observations on seasonal basis, as was the case with Mabahiss. The same trend continued in the more recent surveys, such as the work of FAO/Norway fisheries research vessel Dr. Fridtjof Nansen in 1984 (Stirn et al., 1985; AbdAllah, 2001) and the Joint Global Ocean Flux Study (JGOFS). During the World Ocean Circulation Experiment (WOCE) Hydrographic Program (WHP) in the Indian Ocean, a transect along the main axis of the Gulf was made by the Knor-WHP cruise in August–September 1995. A better coverage of the inner part of the Gulf (i.e. outside the main axis), but limited to the upper 800 m layer, was achieved through the Air-Deployed Expandable Bathythermograph (AXBT) surveys (e.g. Bower et al., 2000).

Data of John Murray–Expedition

The data used in the present work was collected by the Egyptian Research Vessel Mabahiss during the John Murray–Expedition to the Indian Ocean 1933-1934. Methods of measurements and collection of water samples were described by the hydrographer of the Expedition E. F. Thompson in the Scientific Reports of the John Murray–Expedition (Thompson and Gilson, 1937). In his introduction and list of stations, Seymour Sewell, the leader of the Expedition, envisaged the publication of the data set at a later date in the Scientific Reports of the Expedition (Sewell, 1935). However, after many years of persuasion and as late as 1957, Sewell aided by Sir George Deacon, failed to get Thompson, who moved in 1944 to Yale's Bingham Oceanographic Laboratory (Merriman, 1986), to submit the data and his contributions for publication in the Scientific Reports (Morcos, 2004a). At a time when no data centres existed, the data remained in the hands of few scientists. It was offered by Sir George Deacon to the first author (S. Morcos) in 1982 during his work in UNESCO, Paris. Attached to his letter of 8 October 1982, was a 'Potential Temperature θ–Salinity' diagram, for the deep stations of Discovery and Mabahiss in the Indian Ocean. He noted that the Discovery data appear within a systematic narrow band in the diagram, while the more scattered points represent JMME data, thus calling into question the quality of Mabahiss deep observations. He concluded his letter saying "...as the station list is a historical document, it should, I think, be available to Egyptian oceanographers, and I believe it might be a fruitful exercise to make a more detailed comparison with more recent data" (Morcos, 2004b). For more details on digitizing the data see Morcos, 2004b.

The data set of John Murray–Mabahiss Expedition (JMME), was examined critically for their accuracy and to discard obviously bad values of temperature, salinity or oxygen. The data points were checked for outliers, and in few cases, data points that differ from its surrounding points by about three standard deviations were discarded as well as those that do not ensure stability of the water column using T–S diagrams.

Furthermore the data set was evaluated by comparison with the more recent data set of WOCE, which was collected during Knorr WHP in August–September, 1995 (Fig. 1a). Generally, the two data sets show a good agreement in the mode of changes of hydrographic parameters within the water column. On the other hand, divergence exists particularly for those values in the upper 700 m layer, as demonstrated by Fig. 1b–d. This divergence may be attributed to the inherent variability of synoptic data compared to a mean state or to eddy dynamics in this region. Also the seasonal shift in properties may play a role; the observations of Knorr were made in early September and those of Mabahiss in late October.

The Mabahiss data in the Gulf of Aden and Southern Red Sea included 23 stations in late summer (September–October 1933) and 21 stations at the end of winter (April–May 1934). The positions of the stations and the horizontal distribution of the water temperature, salinity, dissolved oxygen and potential density ($\sigma\theta$) are presented for late summer (Fig. 2) and end of winter (Fig. 3)

The four water properties in the complete data set: temperature, salinity. oxygen and density were used to construct four sections: a longitudinal section (stations: 7, 8, 9, 14, 21, 31, 39 for summer and 208, 206, 204, 203, 200, 198, 187, 181 for winter) and three cross sections between the African and Arabian coasts: named as Bab El Mandab section (43°E) through the narrowing upper end of the Gulf (stations: 14, 13, 12 for summer and 200, 201, 202 for winter), Aden section (45°E) in the longitude of Aden (stations: 17, 21, 20, 19, 36 for summer and 199, 198, 197, 195, 196 for winter) and Mouth section (51°E) through the mouth of the Gulf and out through the Socotra Channel (stations: 22, 23, 30, 31, 38, 32 in summer and 173, 174, 175, 181, 182, 183 in winter). The bathymetry of these sections was based on the Admiralty Charts of Gulf of Aden and Southern Red Sea (Charts No. 62954 and 3784) and on the echo-sounding of Mabahiss at the stations' positions. Vertical distributions of temperature, salinity, dissolved oxygen and potential density ($\sigma\theta$) as well as horizontal distributions of these parameters at the surface and at subsurface levels were constructed. In the vertical sections, the upper 500 meter part was blown up at a larger scale (and separated from the deeper part), in order to reveal the details of the relatively strong stratification in the upper layers of the water column. Of this large set of figures, and to avoid repetition of quasi-similar figures, few of the more representative ones in revealing the hydrographic structure of the region were selected for the present discussion. The Ph.D. dissertation of Thompson (1936) included many figures though presented and drawn differently than here. A sample of the cross sections of Thompson were given by Morcos (2004b) in a figure bringing together six cross sections in the longitude of Aden for temperature, salinity and oxygen in two seasons.

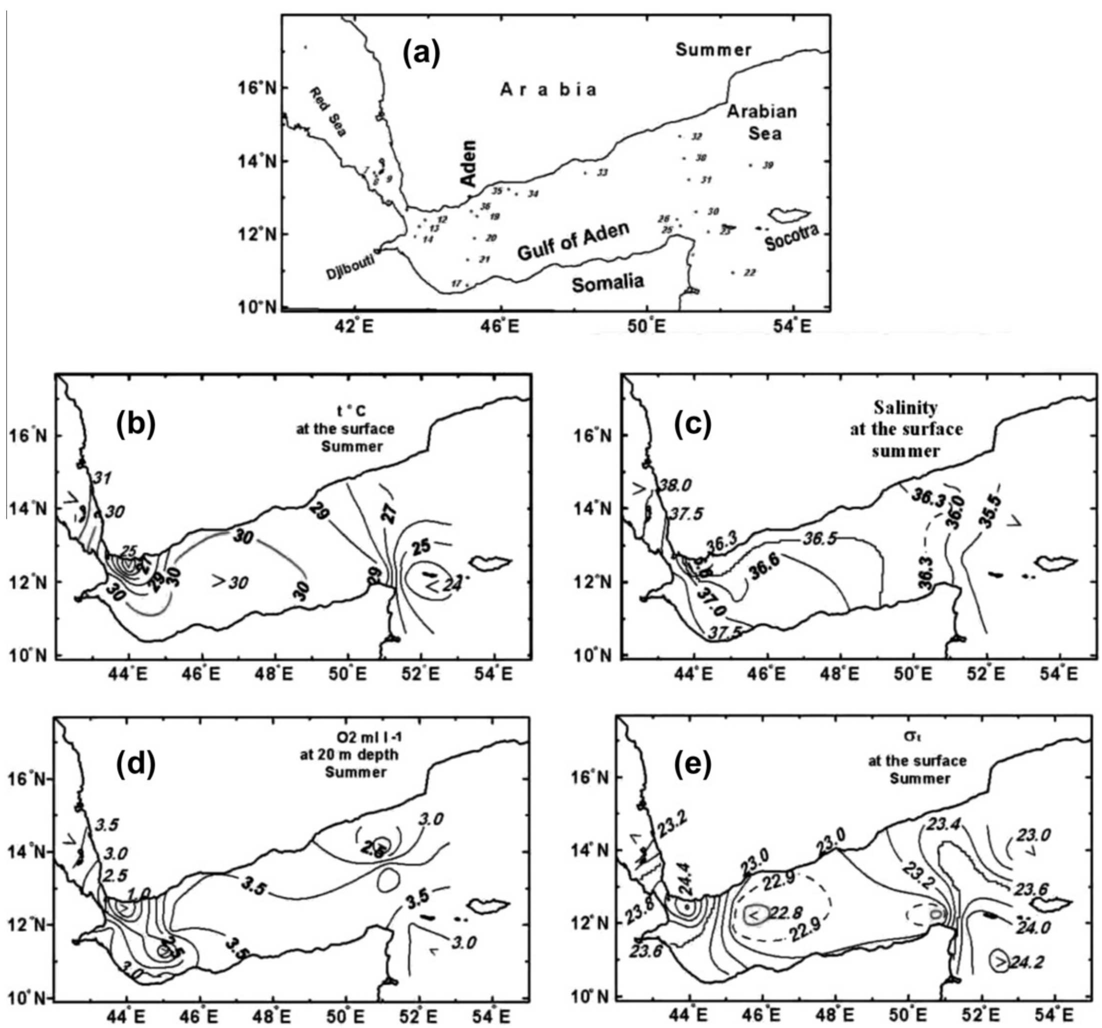


Figure 2 Horizontal distribution of properties, late summer (September–October, 1933), (a) Location of stations, (b) temperature (°C), (c) salinity, (d) dissolved oxygen (ml l^{-1}), (e) density (σt).

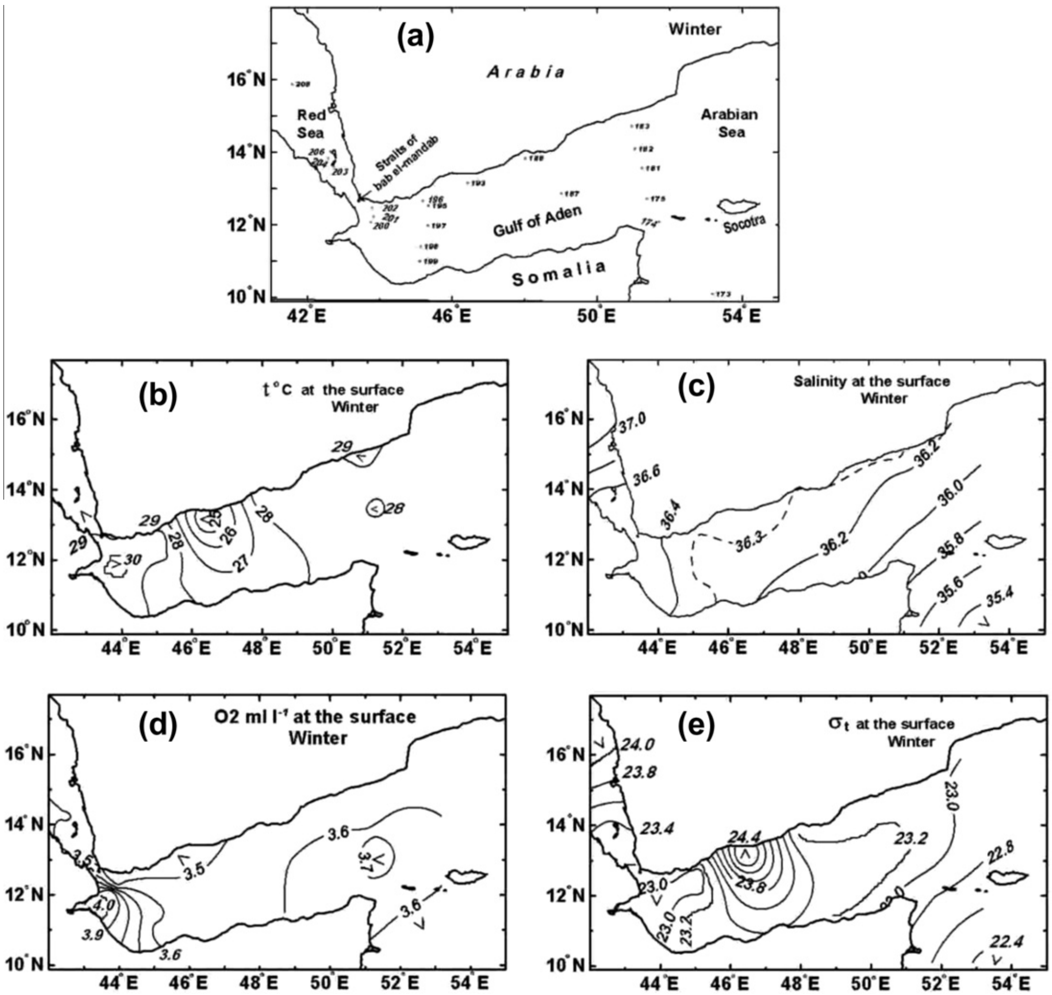


Figure 3 Horizontal distribution of properties, end of winter (April–May, 1934), (a) location of stations, (b) temperature (°C), (c) salinity, (d) dissolved oxygen (ml l^{-1}), (e) density (σt).

Temperature

In summer, a notable feature of the distribution of sea surface temperature is the existence of a relatively much cooler water west of Aden (Fig. 2a). Morcos and Piechura (1990) found a sharp drop in water temperature in Aden Harbour from about 30–32 °C in June to about 20–22 °C in August after studying the daily temperature records of sea water intake in the power house condenser plants in Aden Harbour and Perim Island between 1925 and 1934. The presence of much cooler water in the vicinity of Aden is mainly attributed to upwelling enhanced by several factors such as the deflection of the surface outflow from the Red Sea away from the Arabian coast as a result of the sudden change of orientation of the coast near Bab El Mandab. Upwelling to the west of Aden is also attributed to the convergence in the subsurface west-going flow, near the western extremity of the Gulf of Aden, in response to the rapid decrease of depth in this region. It is known that in the western Gulf of Aden the southwest monsoon wind is less stable and that it ceases earlier (Seriy, 1968), thus limiting its role in developing an Ekman transport upwelling in this region.

Another significant feature of the horizontal distribution of temperature in the surface layer is the existence of a frontal zone near the mouth of the Gulf of Aden. In this region the temperature at the surface (Fig. 2a) and at lower levels to a depth of 30 m decreases rapidly towards the Arabian Sea. This is attributed to the development of an open ocean upwelling across the mouth in response to the positive wind stress curl (Hastenrath and Lamb, 1979).

In summer, the vertical distribution of temperature shows that the mixed layer is very thin (20 m) and a strong thermocline is developed near the surface (Fig. 4a). The temperature along the African coast in the western Gulf of Aden is generally higher than that along the Arabian coast (Fig. 4c). A subsurface inflow of relatively cold water (12–18 °C) from the Gulf of Aden into the Red Sea is evident from Fig. 4a. A part of this west-going flow enters the Strait of Bab El Mandab passing over the sill into the Red Sea and the other part is mixed with warm Red Sea water in the western sector of the Gulf and returning back eastward along the African side (Fig. 4c). Using the results of expandable bathythermographic (XBT) survey along the axis of the southern Red Sea in late October 1969, Johnes and Browning (1971) described a cold water layer at about 100 m depth and temperature as low as 19.1 °C. originating from the Gulf of Aden and reaching further north to 18°10′N. The authors associated the presence of this subsurface cold water with the transition period between summer and winter monsoon seasons.

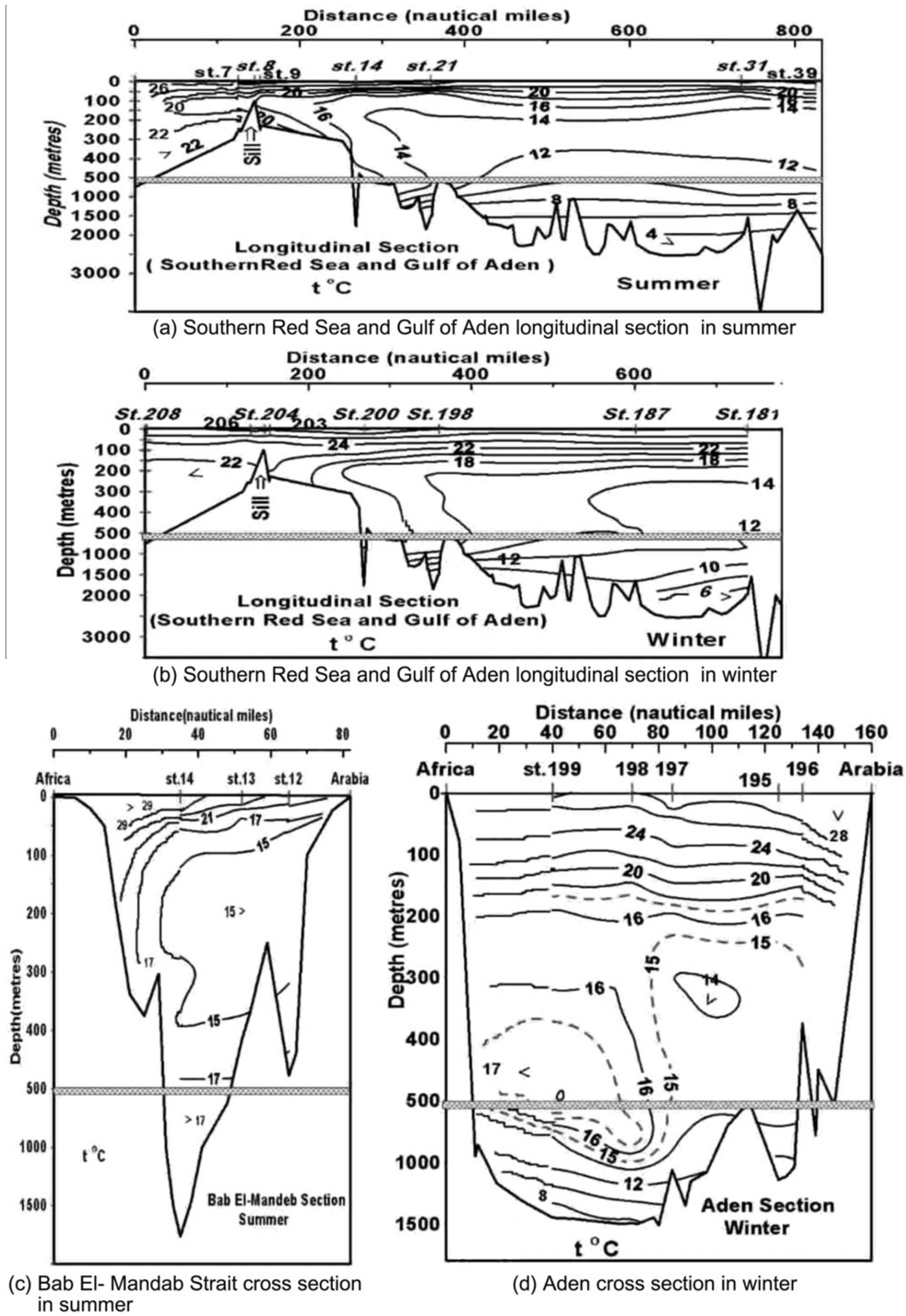


Figure 4 Vertical distributions of temperature. (The upper 500 m layer is enlarged at the vertical scale.) (a) Southern Red Sea and Gulf of Aden longitudinal section in summer. (b) Southern Red Sea and Gulf of Aden longitudinal section in winter. (c) Bab El- Mandab Strait cross section in summer. (d) Aden cross section in winter.

In winter the sea surface temperature is generally lower by 1 or 2 °C than that in summer, except in the upwelling regions where minimum sea surface temperature occurs in summer. In winter, the horizontal distribution of temperature in the upper layer (~150 m) may suggest the existence of a cyclonic eddy in the central part of the Gulf of Aden in agreement with Seriy (1968). Minimum sea surface temperature (25 °C) occurred near the northern edge of the Gulf, while a maximum (30 °C) occupied the most western sector of the Gulf (Fig. 3b).

The vertical distributions of temperature in winter shows that the surface layer is thicker (30–80 m) and the thermo cline is weaker and lies at deeper levels than in summer (Fig. 4b). The mixed layer is thicker along the Arabian coast (Fig. 4d) due to the piling of surface water under the influence of the prevailing northeasterly to easterly winds of the winter monsoon. The cool subsurface west-going flow from the Gulf of Aden into the Red Sea is diminished or blocked by the strong warm deep outflow from the Red Sea. This is evident from the higher values of temperature and the larger area of its influence in the western Gulf of Aden (the left-hand side of Fig. 4b). This deep outflow from the Red Sea spreads, mainly, along the African coast (Fig. 4d) towards the mouth at depths between 200 and 800 m. The temperature at subsurface levels is generally higher than that in summer due to the influence of the strong deep outflow from the Red Sea. In addition, the cool subsurface and deep inflow into the Gulf of Aden from the Arabian Sea is weaker due to the effect of the opposing eastward pressure gradient. This gradient is established as a result of convergence in the western Gulf of Aden under the influence of the prevailing NE winds.

Salinity

In summer, the horizontal and vertical distribution of salinity (Figs. 2c and 5a) showed a surface high saline (37.5) outflow in the upper 50 m layer from the Red Sea into the Gulf of Aden, which spreads mainly along the African coast. Upwelling west of Aden is also evident from the existence of a band of cool and low salinity water in that region (Fig. 2b and c). This is one of several instances where the distribution of salinity is consistent with the distribution of temperature. Near the mouth of the Gulf a sharp salinity gradient is established towards the Arabian Sea (Fig. 2c), which coincides with the thermal front separating the Gulf of Aden warm and high saline water from the cool and less saline upwelled water of the NW Arabian Sea.

Deep Red Sea high saline water starts to appear at depth > 300 m in the western extremity of the Gulf. It occurs within a relatively small area and with a large dilution (< 38.0). This suggests that, in summer the deep outflow from the Red Sea is significantly attenuated by the strong subsurface cool and less saline (< 36.0) inflow from the Gulf of Aden (Fig. 4a and 5a).

In winter, the salinity at the surface (Fig. 3b) and at subsurface levels generally increases towards the Red Sea. The

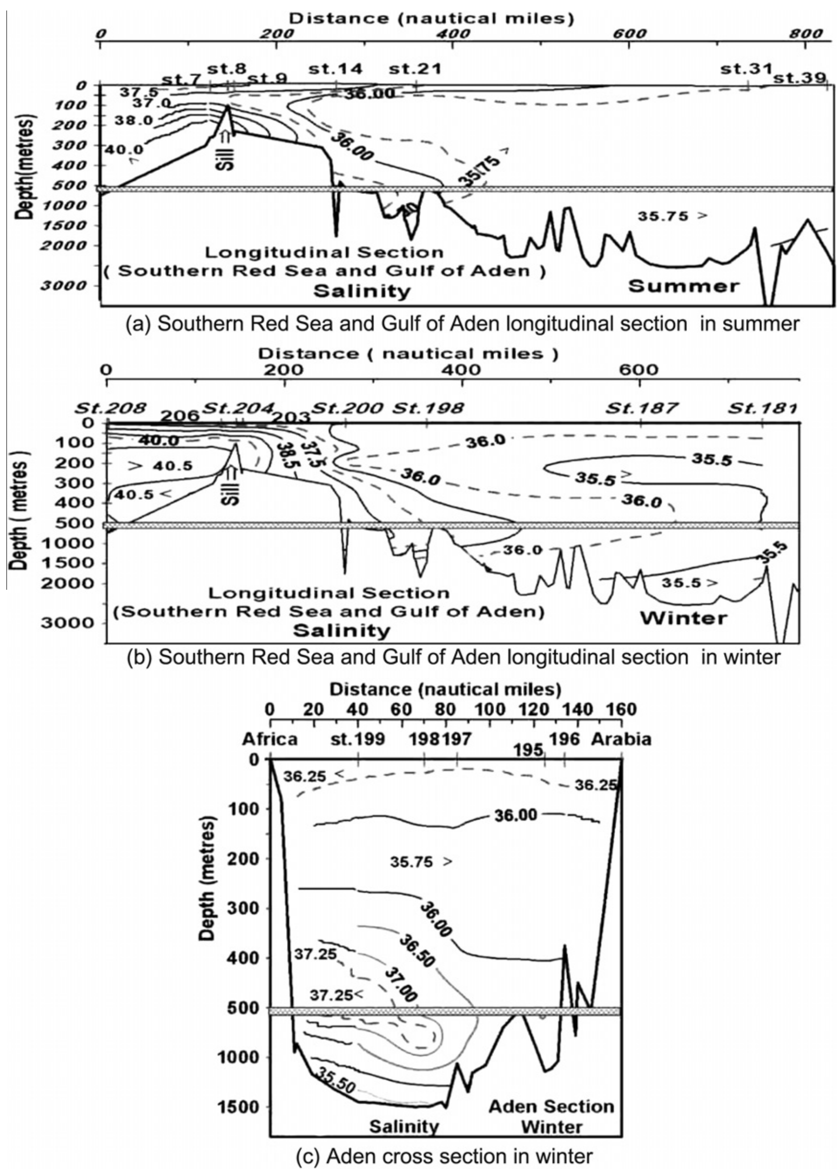


Figure 5 Vertical distribution of salinity. (The upper 500 m layer is enlarged at the vertical scale.) (a) Southern Red Sea and Gulf of Aden longitudinal section in summer. (b) Southern Red Sea and Gulf of Aden longitudinal section in winter. (c) Aden cross section in winter.

salinity in the surface layer to a depth of < 100 m in the western part of the Gulf is generally lower than that in summer due to the monsoonal reversal of surface current. Fig. 5b shows that there is a subsurface inflow with salinity 36.0–37.0 moving up the Gulf into the Red Sea. Also evident from Fig. 5b that there is a deep high saline (38.5–40.5) outflow from the Red Sea, which is more pronounced than that in summer, resulting in a much higher subsurface salinity in the western part of the Gulf of Aden. This deep outflow is branched upon entering the Gulf of Aden into two parts: the major one moves eastward along the African coast, while a smaller part spreads eastward along the Arabian coast at depths between 500 and 1000 m (Fig. 5c). The subsurface cool and less saline water of the Gulf of Aden is blocked at the entrance of the Red Sea by the stronger high saline outflow from the Red Sea (Fig. 5b). In the western Gulf of Aden, salinity is generally higher along the African coast, while in the eastern part, near the mouth, it is higher along the Arabian Side. This suggests that the more saline current, which is moving along the African coast, is deflected near the mouth toward the Arabian side of the Gulf due to the changing topography. The above conclusions are in general agreement with published literature based on ships' observations that followed Mabahiss.

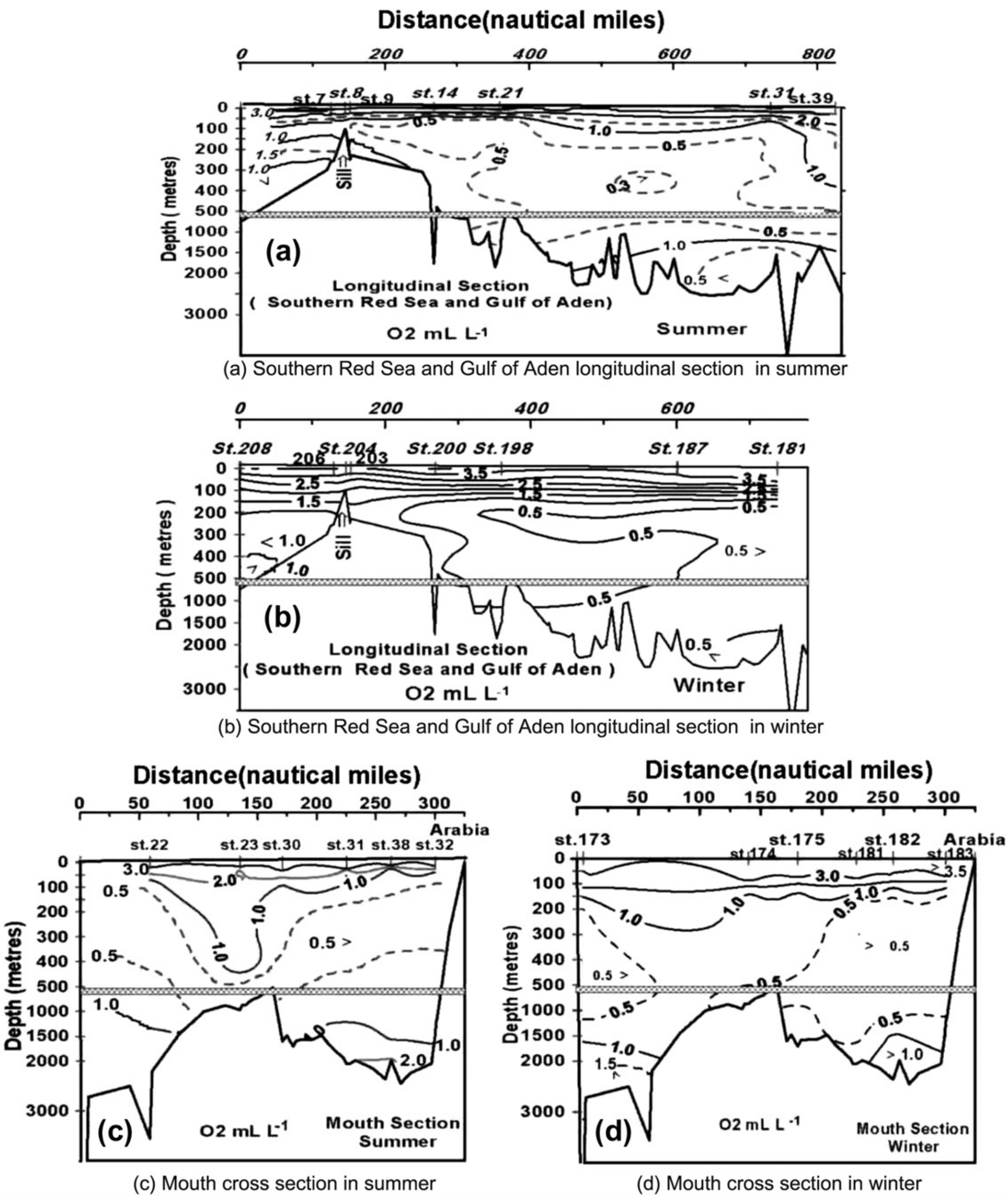
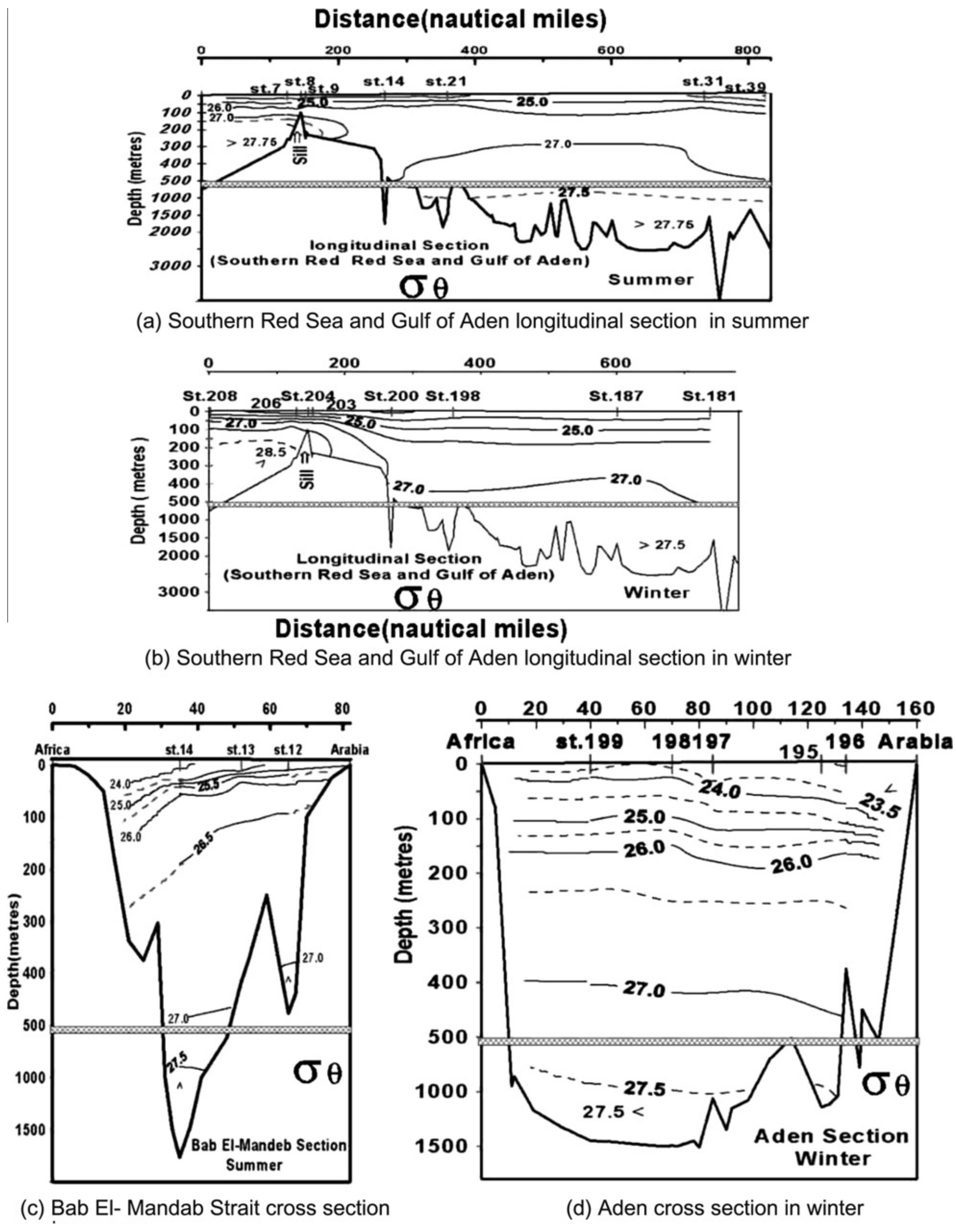


Figure 6 Vertical distribution of dissolved oxygen (ml l^{-1}). (The upper 500 m layer is enlarged at the vertical scale.) (a) Southern Red Sea and Gulf of Aden longitudinal section in summer. (b) Southern Red Sea and Gulf of Aden longitudinal section in winter. (c) Mouth cross section in summer. (d) Mouth cross section in winter.

Dissolved oxygen

In summer, the surface layer down to a depth of 20–30 m is well oxygenated. In this layer oxygen concentration, generally, ranges from 3 to 4 ml l^{-1}. In the upwelling regions, west of Aden and at the northeastern part of the Gulf, oxygen levels can drop to <2 ml l^{-1} at 20 m depth (Fig. 2d). The distribution of dissolved oxygen is consistent with the distribution of temperature and salinity. A subsurface tongue of cool, less saline and low oxygen content (<0.75 ml l^{-1}) water is seen to spread toward the sill into the Red Sea at depths below 50 m (Fig. 4a, 5a and 6a). A strong oxycline is developed in the upper 20–75 m, which mostly coincide with thermocline and halocline. In the upwelling regions the oxycline slopes upward toward the coast (Fig. 6c).

The subsurface water of the Gulf of Aden is poor in oxygen. Minimum values of dissolved oxygen concentration (<0.5 ml l^{-1}) occur at depths 20–700 m (Fig. 6a). This oxygen minimum layer is a characteristic feature of the Arabian Sea and Gulf of Aden. It seems to be the result of excessive consumption combined with oxygen depletion in the water available for renewal before it reaches Gulf of Aden (Swallow, 1984). Dissolved oxygen concentration increases again below the oxygen minimum layer. This is attributed to the effect of Red Sea water of moderate oxygen content ($\approx$1.5 ml l^{-1}) and also to the relatively highly oxygenated (2–3 ml l^{-1}) deep and



(a) Southern Red Sea and Gulf of Aden longitudinal section in summer

(b) Southern Red Sea and Gulf of Aden longitudinal section in winter

(c) Bab El- Mandab Strait cross section in summer

(d) Aden cross section in winter

Figure 7 Vertical distribution of density (σt). (The upper 500 m layer is enlarged at the vertical scale.) (a) Southern Red Sea and Gulf of Aden longitudinal section in summer. (b) Southern Red Sea and Gulf of Aden longitudinal section in winter. (c) Bab El- Mandab Strait cross section in summer. (d) Aden cross section in winter.

bottom inflow from the Arabian Sea. At these levels, dissolved oxygen content generally decreases toward the center of the Gulf (Fig. 6a). In the western Gulf of Aden, water at depths below 400–500 m along the African side has higher oxygen content, whereas in the eastern sector this situation is reversed (e.g. Station 30 near the African coast in Fig. 6c). At greater depths in the eastern part of the Gulf (and contrary to the situation in the western part), higher oxygen values are found near the Arabian side (Stations 32–38) than the African side (Stations 30–31). This also suggests that the relatively highly oxygenated deep and bottom waters of the Arabian Sea enter the eastern Gulf of Aden, mainly, along the Arabian side of the Gulf and are later deflected in the western part of the Gulf toward the African side due to the changing bottom topography.

In winter, the dissolved oxygen concentration at the surface is slightly higher than that in summer. It ranges from 3.7 to 4.2 ml l^{-1} (Fig. 3d), and the well-oxygenated surface layer is thickened. The deep outflow of moderate oxygen concentration ($\approx$ 1.5 ml l^{-1}) from the Red Sea is more pronounced than that in summer (Figs 6b and a). Also in winter, the oxycline occurs at greater depths (> 100 m) than in summer. In the western Gulf of Aden, oxygen minimum layer is relatively thin and lies at shallower depths, whereas in the eastern sector it is thicker and occurs at deeper levels (Fig. 6b). The oxygen content of the deep and bottom water in the eastern Gulf of Aden (Mouth Section) is smaller in winter (Fig. 6d) than that in summer (Fig. 6c), whereas in the western sector of the Gulf it is larger in winter. This indicates that in winter the deep flow into the Gulf of Aden from the Arabian Sea, which is characterized by relatively high dissolved oxygen, is greatly reduced, whereas the inflow of moderately high oxygenated Red Sea water into the Gulf of Aden is significantly increased. In the western Gulf of Aden, at depths 300–400 m, dissolved oxygen concentration is higher along the African coast due to the effect of deep outflow from the Red Sea.

Density

In summer, the horizontal distribution of density at the surface (σt) (Fig. 2e) suggests the existence of an anticyclonic gyre in the central part of the Gulf of Aden. The upwelling developed to the west of Aden is evident by the sharp increase of density in this region. Near the mouth, a front is established separating the light surface water of the Gulf of Aden from the cool upwelled water of the NW Arabian Sea, which is in agreement with Johns et al. (1999). In the region between Socotra and the African coast of the Arabian Sea, the distribution of isopycnals (Fig. 2e) also suggests the existence of a cyclonic eddy in this region of Somali current system, which is according to Bower et al. (2002) is rich with high energetic eddies.

The surface layer in summer is very thin and a sharp pycnocline is developed at its lower boundary (Figs 7a and c). The downward plunging of isopycnals near the sill (Fig. 7a) indicates a sinking of Red Sea water ($\sigma\theta$ > 26.5) into the Gulf of Aden. At the sill, it seems that the deep outflow from the Red Sea is nearly blocked by the subsurface inflow from the Gulf of Aden ($\sigma\theta$ < 26.5) into the Red Sea (Fig. 7a).

In winter, the distribution of density at the surface (σt) (Fig. 3e) and at sub-surface levels (~150 m depth) suggests the existence of a cyclonic eddy in the central part of the Gulf of Aden with its center close to the Arabian coast. A deep reaching (nearly to 1000–2000 m depth) cyclonic eddy was observed (February 2001) in the central part of the Gulf of Aden. It is centered between 46° and 47° E and at about 12°15′N and spans much of the width of the gulf, with a diameter of ~225 km and a maximum speed of 0.4 m s^{-1} (Bower et al., 2002).

Near the sill, the deep outflow from the Red Sea ($\sigma\theta$ > 26.5) is indicated by the plunging of isopycnals into the Gulf of Aden (Fig. 7b). This deep outflow from the Red Sea into the Gulf of Aden is more evident than that in summer and it seems to have come from depths 100–200 m in the Southern Red Sea. Generally, the surface layer is thicker than that in summer, particularly along the Arabian coast. This is more obvious at Aden section (Fig. 7d) and is attributed to the convergence in the surface layer of the Gulf of Aden under the influence of NE monsoon winds.

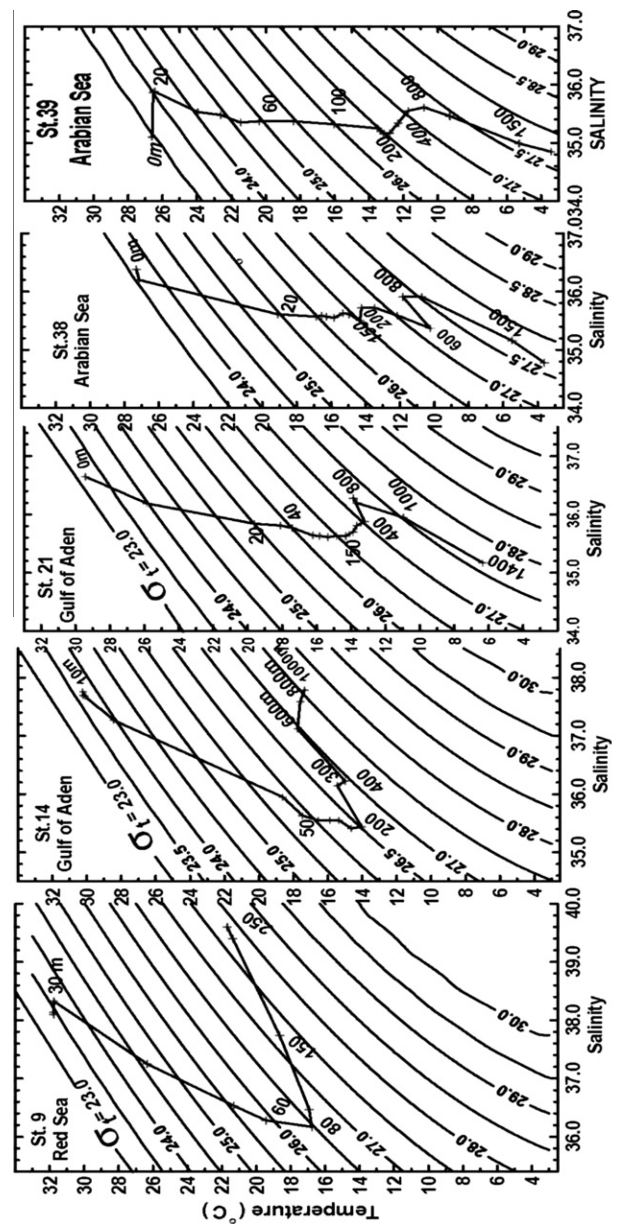


Figure 8 T–S diagrams in summer at stations: 9 (southern Red Sea), 14,21 (Gulf of Aden), and 38,39 (Arabian Sea).

Water masses

Water masses in the Gulf of Aden were studied using T–S diagrams at some selected stations along the median line extending from the southern Red Sea through the Gulf of Aden into the Arabian Sea in both summer and winter seasons. Generally, there are several water masses in the Gulf of Aden, which are characterized by marked seasonal and spatial changes in their characteristics.

Gulf of Aden surface water mass (GASW)

This water mass (GASW) occupies the uppermost layer, ranging in depth from 20 m down to 150 m. The lower boundary of the GASW can be placed along the isopycnal surface 25.0–25.5 (Fig. 8 and Fig. 9). This water mass is characterized by high temperature (18–30 °C), salinity (35.6–37.8) and fairly high oxygen (3–4 ml l^{-1}). The surface water is considered as a mixture of:

i. high salinity southern Red Sea surface water driven into the Gulf of Aden during summer (June–September);
ii. relatively low salinity surface water from the Arabian Sea entering the Gulf of Aden during winter (November–April);
iii. upwelled water in the Gulf of Aden (during summer), which are characterized by low temperature, low salinity and low oxygen content.

These three types of water undergo strong mixing at different proportions and further acquire different characteristics owing to intensive heating and evaporation.

The hydrographic characteristics and the extent of the GASW exhibit seasonal and spatial changes. Generally the seasonal variations of temperature is very small due to the small seasonal changes of insolation at lower latitudes. Contrary to temperature, the salinity of the GASW does exhibit marked seasonal changes. Salinity is generally higher in summer than in winter, particularly in the western Gulf of Aden (Fig. 8, Station 14 and Fig. 9, Station 200) This pronounced variation of salinity is attributed to the high salinity Red Sea water driven in summer into the Gulf of Aden under the influence of the prevailing NNW winds over the entire Red Sea (Khmitsa, 1968; Morcos, 1970; Patzert, 1974; Poisson et al., 1984; Murray and Johns, 1997). The spatial variations of the hydrographic characteristics of GASW are relatively small and most of the variations of the water characteristics are found near its boundaries with the Red sea and the Arabian Sea (Fig. 8 and Fig. 9).

During summer, the surface layer is very thin (Fig. 9) due to the divergence in the surface layer induced by the prevailing strong southwest monsoon. It occupies only the upper 20–40 m of water along the Arabian coast and up to 70–80 m along the African coast (Khmitsa, 1968; Stirn et al., 1985). In winter the surface layer is thicker, it extends from the surface down to 125–150 m (Fig. 9), due to the convergence in the surface layer under the influence of the prevailing northeast monsoon. The movement of the SW undergoes a biannual reversal associated with the monsoonal reversal of wind. In winter, the easterly winds of the Gulf of Aden drive the surface water westward into the Red Sea. While in summer, the prevailing southwesterly to westerly winds direct the surface water mainly eastward from the Gulf into the Arabian Sea (Khmitsa, 1968; Seriy, 1968).

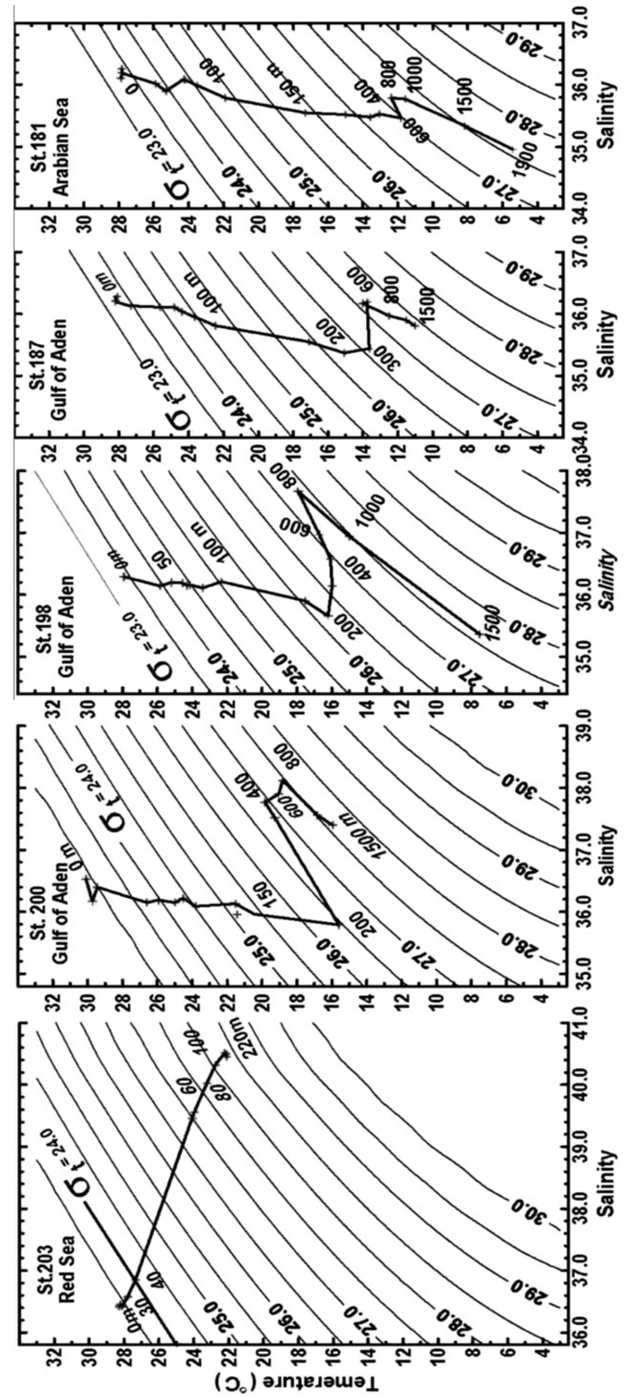


Figure 9 T–S diagrams in winter at stations 203 (southern Red Sea), 200,198,187 (Gulf of Aden), and 181 (Arabian Sea).

Gulf of Aden subsurface water mass (GASSW)

Below the upper saline surface water down to a depth of about 600 m exists a layer of intermediate minimum salinity and minimum oxygen content. This oxygen minimum layer has its source in the northern Arabian Sea (Olson et al., 1993). The

GASSW has a temperature of 11–19 °C and salinity of 35.4–36.5 (Fig. 8 and Fig. 9).

The minimum salinity layer originates in the Gulf of Aden from the advection in the subsurface layer of low salinity Arabian Sea water which is sandwiched between the warm saline surface water above and the high salinity Red Sea water beneath (Khmitsa, 1968). Along the Arabian side of the Gulf, the general movement of this water mass is towards Bab El Mandab. Part of this water mass enters the Red Sea as a subsurface cool and low saline inflow in summer or as part of surface flow in winter. The other part, of the GASSW is turned back along the African coast with considerable mixing with high salinity Red Sea water.

The Gulf of Aden subsurface water mass shows remarkable seasonal changes. In summer, the upper boundary of the GASSW lies at shallower depths (< 40 m), its temperature and salinity generally have lower values than in winter (Fig. 8 and Fig. 9). The nutrient content of this layer is very high, while its oxygen content is very low particularly in summer, usually below 1 ml l^{-1} and very often below 0.5 ml l^{-1} (Stirn et al., 1985)]. In the Gulf of Aden, the core of the GASSW generally lies at depths between 150 m and 250 m and has a density (σt) of about 26–27 (Fig. 8 and Fig. 9). In summer, the core of GASSW lies at shallower levels and generally characterized by lower temperature, salinity and oxygen content than in winter. This is due to its ascent in summer and decent in winter under the influence of the prevailing wind in the corresponding seasons.

Red Sea water mass (RSW)

The vertical structure of water in the Gulf of Aden is characterized by the existence of a layer of intermediate maximum salinity (35.65–38.10) and relatively high temperature (11–19 °C) at depths between 200 and 1000 m (Fig. 8 and Fig. 9). This intermediate maximum salinity is due to the inflow of warm and more saline water from the Red Sea which enters the Gulf of Aden as a deep current through the Strait of Bab El Mandab (Khmitsa, 1968; Seriy, 1968; Siedler, 1968; Morcos, 1970; Patzert, 1974; Stirn et al.; 1985; Millard and Soliman, 1986; Murray and Johns, 1997; Beal et al., 2000; Bower et al., 2000; AbdAllah, 2001; Bower et al., 2002; Sofianos and Johns, 2002). More recently, Sofianos and Johns (2002,2003) traced a large proportion (65%) of this saline outflow into the Gulf of Aden to the Red Sea Outflow Water (RSOW) which is produced in a permanent cyclonic gyre in the northern Red Sea.

The Red Sea outflow appears in JMME section in the Gulf of Aden as a deep high saline (38.5–40.5) layer in winter (Fig 5b), more conspicious than in summer (Fig. 5a). The core layer of the Red Sea water (RSW) has a density (σt) of 27.0–27.5 (Fig. 8 and Fig. 9) and lies at depths below 300 m in the western part of the Gulf of Aden (Fig. 8, Stations 14 & 21), and at deeper levels (> 900 m) towards the east (Fig. 8, Station 31 and Fig 9, Station 181). Moving toward the Arabian Sea, the layer of RSW gradually becomes thinner and lower in temperature, salinity and oxygen content due to the turbulent exchange with the surrounding layers. The hydrographic characteristics of the RSW have been shown to vary seasonally due mainly to the seasonal variability in the water exchange between the Red Sea and the Gulf and eddies dynamics (Maillard and Soliman, 1986; Murray and Johns, 1997; Beal et al., 2000; Bower et al. 2000; Bower et al., 2002; Siddall et al., 2002). The core layer of the RSW has a higher temperature, salinity (Fig. 8 and Fig. 9) and oxygen content in winter than in summer due to the higher inflow of Red Sea water into the Gulf of Aden in winter season. Fedorov and Meshchanov, 1988 indicated that, in winter, Red Sea Water has a multilayered structure in the Gulf of Aden. According to Bower et al. (2000) Red Sea outflow into the Gulf of Aden results in product water with significantly different densities which probably contribute to the multilayered structure of the Red Sea product water. In the present work, the available data indicate a two layered structure of Red Sea Water in the western Gulf of Aden in winter season .The core depth of the first layer lies at about 400 m, and the deeper one at a depth of 800 m (Fig. 9, Station 200).

As noted before, the deep outflow from the Red Sea is branched upon entering the Gulf of Aden into two parts flowing downslope in two channels, the major part moves eastward along the African coast, while a smaller part spreads eastward along the Arabian coast at depths between 500 and 1000 m (Fig. 5c). The outflow in the two channels was investigated in 2001 during the Red Sea Outflow Experiment REDSOX-1 in the winter season of maximum outflow, and during REDSOX-2 in the summer season of minimum outflow. The results of these cruises provided the material for recent studies on mixing and entrainment in the Red Sea outflow plume, giving details on the plume structure (Peters et al., 2005) and on the turbulance characteristics (Peters and Johns, 2005). The vertical structure of the Red Sea plume is emphasised. A mixed or weakly stratified "bottom layer" is distinguished from the overlying, strongly stratified and highly sheared "interfacial layer". Both layers differ in magnitude, characteristics and behaviour.

Persian Gulf water mass (PGW)

According to Sen Gupta and Qasim (1985), the PGW has a density (σt) of 26.5 and can be identified in the Arabian Sea from a depth range of 100–300 m. This water mass is identified near the mouth of the Gulf of Aden, particularly in summer, as a secondary maximum salinity (35.65–35.75) at depths between 150 and 300 m as shown in the T-S diagram of station 38 (Fig. 8). Generally, RSW and PGW can be traced at intermediate depths over large areas of the Indian Ocean owing to their extreme temperature–salinity characteristics (Varma et al., 1980; Premchand et al., 1986; Shapiro and Meschanov, 1991; Beal et al., 2000; Bower et al, 2000).

Gulf of Aden Deep water mass (GADW)

This water mass, of circumpolar origin, is transported to the northwest Arabian Sea and Gulf of Aden by a deep boundary current (Warren, 1981). Ivanenkov and Gubin (1960) termed this water mass as the North Indian Ocean Deep Water that can be identified from a depth range 1000–2000 m down to the bottom. The Gulf of Aden, particularly its western part, is characterized by a high bottom water temperature than any other part of the Indian Ocean (Khmitsa, 1968). This may be due to the higher bottom heat flux (Herzen, 1963).

The GADW is generally traced to the relatively cool (3–10 °C) and low saline (34.85–35.5) inflow from the Arabian Sea at depths greater than 1000 m. As the GADW moves westward (i.e. from the right to the left side of Fig. 8 and Fig. 9) its temperature and salinity increases due to mixing with the Red Sea water and becomes very poor in oxygen due to oxidation of organic matters. The GADW also shows seasonal changes. In summer, it is cooler, less saline and higher in oxygen content than in winter, an evidence of the stronger summer inflow from the Arabian Sea

Discussion and conclusions

The studies of E. F. Thompson, the hydrographer of the JMME, on the Gulf of Aden, Arabian Sea, and Gulf Oman remained virtually unknown in his unpublished dissertation in the University of Cambridge (Thompson, 1936), until they were released to us fifty years later.

The data collected during the John Murray–Expedition to the Indian Ocean 1933–1934 were used to investigate the oceanographic conditions, water masses and circulation in the Gulf of Aden and Southern Red Sea. The purpose of our study is to establish the state of art of oceanographic knowledge before the Second World War, an era that provided the main source material upon which the landmark book of Sverdrup et al (1942) was based. The conclusions reached from the present work are in a good agreement with those obtained from the more recent studies Although our study benefited from the recent advances in our knowledge of the region, the broad oceanographic features of the Gulf of Aden could have been known years ago, if the data and results of JMME were timely published following the return of the expedition.

We realize that the number of Mabahiss stations are not as abundant as present day surveys. It may be difficult to draw conclusive interpretation from such short set of data, although it is the most comprehensive data set before the International Indian Ocean Expedition (IIOE) of the early 60's. We should remember that the findings of the major oceanographic expeditions of that era were based on much limited stations than the present day rich coverage. Using these limited data sets, older generations of oceanographers developed the broad features and concepts of the global ocean. Many of these features and concepts are continually tested by todays oceanographers in their quest to further our knowledge using new technologies and approaches.

The unpublished study of Thompson (1936) in his Ph.D. dissertation on the Gulf of Aden, was completely dependent in its interpretations on the seasonal reversal of the monsoons. Recent studies tend to attribute the oceanographic changes between the summer and winter data to seasonal shift in circulation, a conclusion that is in general agreement with the published literature in the last three decades. One may further argue that a seasonal circulation shift may be at work in the far western Gulf near Bab El Mandab Strait, but perhaps not as obvious in the eastern part where it opens to the Arabian Sea. Johns et al (1999) noted that the Gulf of Aden is seen in satellitre images to be''choked up'' with large eddies, mostly anticyclones. They appear to propagate westward from the mouth of the Gulf toward the Red Sea and their origin may be linked to the propagation and decay of eddy features in the western Arabian Sea. The more recent literature, such as that by Bower et al (2002) details the near full water column eddies present in the Gulf that ''stirs''the waters there. This introduces a new element in our interpretation that may suggest that eddies have more to do, than was thought before, with the changes in the water mass structure between summer 1933 and winter 1934.

With the above statement in mind and within the limits of this historical data, our study revealed significant spatial and seasonal changes in the hydrographic structure and circulation in this region. During SW monsoon (summer) upwelling developed to the west of Aden and a front is established across the mouth of the Gulf opening to the Arabian Sea. These two regions are important for fishery industry. In summer, the deep outflow from the Red Sea into the Gulf of Aden is significantly diminished, whereas the intermediate and deep inflows from the Arabian Sea into the Gulf are increased. Also in summer, the distribution of hydrographic properties suggests the existence of an anticyclonic eddy in the upper 20 m near the center of the Gulf of Aden.

The deep outflow from the Red Sea into the Gulf of Aden is significantly increased during NE monsoon (winter), whereas the inflow from the Arabian Sea into the Gulf is decreased. The surface circulation is reversed in winter and a cyclonic gyre is detected in the central part of the Gulf of Aden. At sub-surface and at deeper levels the circulation is generally cyclonic in both seasons.

The water masses in the Gulf of Aden show significant spatial and seasonal changes in their hydrographic structure mainly due to the monsoonal reversal of wind and eddy dynamics. Five water masses are identified as:

I. Gulf of Aden Surface Water Mass (GASW) is characterized by its high temperature (18–30 °C), high salinity (35.6–37.8) and fairly high oxygen content (3–4 ml l^{-1}). This water mass extends from the surface down to 20–150 m depth. The lower boundary of this water mass can be placed along the isopycnals surface 25.0–25.5.
II. Gulf of Aden Subsurface Water Mass (GASSW) has a temperature of 11–19 °C and salinity of 35.4–36.5. The core of the GASSW generally lies at 150–250 m and has a density (σt) of about 26.0–27.0.
III. Red Sea Water (RSW) has a salinity of 35.65–38.10 and a temperature of 11–19 °C. The core layer of RSW has a density (σt) of 27.0–27.5 and lies at depth of 400 m, in the western Gulf of Aden, to 900 m near the mouth of the Gulf.
IV. Persian Gulf Water Mass (PGW) has a density (σt) of 26.5 and can be identified near the mouth of the Gulf of Aden, particularly in summer as an intermediate layer of a secondary maximum salinity (35.65–35.75) at depths between 150 m and 300 m.
V. Gulf of Aden Deep Water Mass (GADW) The GADW is generally traced to the relatively cool (3–10 °C) and low saline (34.85–35.5) inflow from the Arabian Sea at depths greater than 1000 m.

The subsurface water in the Gulf of Aden is poor in oxygen (<0.5 ml l^{-1}). The de-oxygenation problem becomes more significant in summer, when water of anoxic oxygen concentration occurs at shallow depths (<20 m), particularly in the upwelling regions. The proper management of the marine environment and living resources of the Gulf of Aden requires the understanding of the deoxygenation problem and its catostrophic effects on the ecosysztem as well as the variability in the oceanographic conditions of the region.

References

AbdAllah, A.M., 2001. Oceanographic conditions off the Southern Coast of Yemen during South-West Monsoon. Bulletin of the Faculty of Science, University of Alexandria, Egypt. 41 (1–2), 33–45.

Beal, L.M., Ffield, A., Gordon, A.L., 2000. Spreading of Red Sea overflow waters in the Indian Ocean. Journal of Geophysical Research 105 (C4), 8549–8564.

Bogdanova, A.K., 1966. Hydrological characteristics of the Red Sea and the Gulf of Aden according to the observations of the research vessel "Academik Kovalevsky". Okeanol. Isled.15, 45–68 (in Russian).

Bower, A.S., Hunt, H.D., Price, J.F., 2000. Character and dynamics of the Red Sea and Persian Gulf outflows. Journal of Geophysical Research 105 (C3), 6387–6414.

Bower, A.S., Fratantoni, D.M., Johns, W.E., Peters, H., 2002. Gulf of Aden eddies and their impact on Red Sea Water. Geophysical Research Letters 29 (21), 1–4.

Fedorov, K.N., Meshchanov, S.L., 1988. Structure and propagation of Red Sea Waters in the Gulf of Aden. Oceanology 28 (3), 279–284.

Hastenrath, S., Lamb., P.J., 1979. Climatic Atlas of the Indian Ocean. Part I: Surface Climate and Atmospheric Circulation. University of Wisconsin Press, pp. 19 + 97 charts.

Herzen, R., 1963. Geothermal heat flow in the Gulfs of California and Aden. Science, 140.

Ivanenkov, V.N., Gubin, F.T., 1960. Water masses and hydrochemistry of the western and southern parts of the Indian Ocean. Trudy Morkii Gidrofiz. Ins. Akad. Nauk. SSSR 22, 33–115 (in Russian).

Johnes, E.N., Browning, D.G., 1971. Cold water layer in the southern Red Sea. Limnology and Oceanography 16 (3), 503–509.

Johns, W. E., Jacobs, G.A., Kindle, J.C., Murray, S.P., Carron, M., 1999. Arabian Marginal Seas and Gulfs: Report of a Workshop held at Stennis Space Center, Miss. 11–13 May, 1999. University of Miami RSMAS, Technical Report 2000-01, 60.

Khmitsa, V.A., 1968. Hydrologic structure of the Gulf of Aden. Okeanol 8, 379–402 (in Russian).

Maillard, C., Soliman, G., 1986. Hydrography of the Red Sea and exchanges with the Indian Ocean in summer. Oceanologica Acta. 9 (3), 249–269.

Merriman, D. 1986. E. F. Thompson. Biographical notes on the principal participants. In: Rice, A.L. (Ed.), Deep-Sea Challenge, The John Murray/Mabahiss Expedition to the Indian Ocean 1933–1934. UNESCO, Paris, 278–280.

Mohamed, A.F., 1940. The Egyptian exploration of the Red Sea. Proceedings of the Royal Society of London, Series B 128 (852), 306–316.

Morcos, S.A., 1970. Physical and Chemical Oceanography of the Red Sea. In: Barnes, H. (Ed.), Oceanography and Marine Biology, Annual Review, Vol. 8. George Allen and Unwin, London, pp. 73–202.

Morcos, S., 2004a. The saga of Seymour Sewell and the scientific reports of the John Murray Expedition. Ocean Challenge 13 (1), 15–16.

Morcos, S., 2004b. Data set of John Murray/Mabahiss Expedition to the Indian Ocean (1933–1934). In: Morcos, S. et al. (Eds.), Ocean Sciences bridging the millennia, A spectrum of historical accounts. Proceedings of the Sixth International Congress on History of Oceanography (ICHO VI), Qingdao, China, August 1998, UNESCO/IOC and China Ocean Press, Paris, 79–102.

Morcos, S., Piechura J., 1990. From the Archives of the John Murray/Mabahiss Expedition: Strong summer cooling of surface water revealed by historic data in Gulf of Aden and Bab El Mandab, In: Lenz, W., Deacon, M. (Eds.), Ocean Sciences: Their history and relation to man, Proceedings of the Fourth International Congress on History of Oceanography (ICHO IV), Hamburg, Germany. September 1987, Deutsche Hydrographische Zeitschrift, Reihe B, Nr. 22, Hamburg, 378–390.

Morcos, S., Soliman, G.F., 1974. Circulation and deep water formation in the Northern Red Sea in winter (Based on R/V Mabahisss sections, January–February, 1935). In L'Océanographie physique de la Mer Rouge, pp. 91–103, Centre National pour l'Exploration des Océans (CNEXO), Paris, 91–103.

Murray, S.P., Johns, W., 1997. Direct observations of seasonal exchange through the Bab el Mandab Strait. Geophysical Research Letters 24 (24), 2557–2560.

Olson, D.B., Hitchcock, G.L., Fine, R.A., Warren, B.A., 1993. Maintenance of the low-oxygen layer in the central Arabian Sea. Deep-Sea Research Part I 40, 673–685.

Osman, M.M., 1985. Water exchange between the Red Sea and Gulf of Aden. International Symposium, Upwelling W. Africa. Inst. Invest. PESQ Barcelona 1, 205–212.

Patzert, W.C., 1974. Wind-induced reversal in the Red Sea circulation. Deep-Sea Research 21, 109–121.

Peters, H., Johns, W.E., Bower, A.S., Fratantoni, D.M., 2005. Mixing and Entrainment in the Red Sea outflow plume. Part I: Plume structure. Journal of Physical Oceanography 35, 569–583.

Peters, H., Johns, W.E., 2005. Mixing and entrainment in the Red Sea outflow plume. Part II Turbulance charaeristics. Journal of Physical Oceanography 35, 584–600.

Poisson, A., Morcos, S., Souvermezoglou, E., Papaud, A., Ivanoff, A., 1984. Some aspects of biogeochemical cycles in the Red sea with special reference to new observations made in summer 1982. Deep-Sea Research Part A 31 (6–8A), 707–718.

Premchand, K., Sastry, J.S., Murty, C.S., 1986. Water mass structure in the western Indian Ocean. Part 2: The spreading and transformation of the Persian Gulf Water and Part 3: The spreading and transformation of the Red Sea water masses. Mausam 37, 179–186, and 317–324.

Sen Gupta, R., Qasim S.Z., 1985. The Indian Ocean – an environmental overview IOC/UNESCO Workshop, Report 37, 9–39.

Seriy, V.V., 1968. Peculiarities of seasonal variations in hydrological condition in the Gulf of Aden. Trudy VNIRO 64-AZCHERNIRO 28, 117–129 (in Russian).

Sewell, R.B.S., 1935. Introduction and List of Stations, The John Murray Expedition 1933–1934, Scientific Reports. British Museum (Natural History) London 1 (1), 1–41.

Shapiro, G.I., Meschanov, S.L., 1991. Distribution and spreading of Red Sea Water and salt lens formation in the northwest Indian Ocean. Deep-Sea Research Part A 38, 21–34.

Siddall, M., Smeed, D.A., Matthieson, S., Rohling, E.J., 2002. Modeling the seasonal cycle of the exchange flow in Bab El Mandab (Red Sea). Deep-Sea Research I 49 (9), 1551–1569.

Siedler, G., 1968. Schichtungs-und Bewegungsverhaltnisse am Sudausgang des Roten Meeres. "Meteor" Forschungsergebnisse, Reihe A, Heft 4, 1–76.

Smith, R.L., 1968. Upwelling. In: Barnes, H. (Ed.), Oceanography and Marine Biology, Annual Review, Vol. 6. George Allen and Unwin, London, pp. 11–46.

Sofianos, S.S., Johns, W.E., 2002. An oceanic general circulation model (OGCM) investigation of the Red Sea circulation, 1. Exchange between the Red Sea and the Indian Ocean. Journal of Geophysical Research 107(C11), 3196, http://dx.doi.org/10.1029/2001JC001184, 2002.

Sofianos, S.S., Johns, W.E. 2003. An oceanic general circulation model (OGCM) investigation of the Red Sea circulation, 2. Three-dimensional circulation in the Red Sea. Journal of Geophysical Research 108(C11), 3166, http://dx.doi.org/10.1029/2001JC001185, 2003.

Sofianos, S.S., Johns, W.E., Murray, S.P., 2002. Heat and Freshwater budgets in the Red Sea from direct observations at Bab el Mandeb. Deep-Sea Research Part II 49, 1323–1340.

Souvermezoglou, E., Metzel, N., Poisson, A., 1989. Red Sea budgets of salinity, nutrients and carbon calculated in the Strait of Bab-El-Mandab during the summer and winter seasons. Journal of Marine Research 47, 441–456.

Stirn, J., Edwards, R., Piechura, J., Savich, M., Ghaddaf, M., Fadel, M., Mutlaq, F., Sabih, O., Sayed, A., Shaher, S., Zubairi, Z., 1985. Oceanographic conditions, pelagic productivity, and living resources in the Gulf of Aden. IOC/UNESCO Workshop Report 37, 255–297.

Sverdrup, H.U., Johnson, M.W., Fleming, R.H., 1942. The Oceans, their Physics Chemistry and General Biology. Prentice-Hall, Inc., New York, p 1087.

Swallow, J.C., 1984. Some aspects of the physical oceanography of the Indian Ocean. Deep-Sea Research. Part A 31 (6–8A), 639–650.

Thompson, E.F. 1936. The physical and chemical factors of the environment of animals in the Red Sea, the Gulf of Aden, the Gulf of Oman, and the Northwest Indian Ocean. Ph.D. Dissertation, University of Cambridge, United Kingdom Unpublished typescript, 220 pages.

Thompson, E.F., Gilson, H.C., 1937. Chemical and physical investigations, Introduction, The John Murray Expedition 1933–1934, Scientific Reports. British Museum (Natural History) London 2 (2), 15–20.

Thompson, E.F., 1939a. The general hydrography of the Red Sea. The John Murray Expedition 1933–1934. Scientific Reports. British Museum (Natural History) London 2 (3), 83–103.

Thompson, E.F., 1939b. The exchange of water between the Red Sea and the Gulf of Aden over the "Sill". The John Murray Expedition 1933–1934, Scientific Reports. British Museum (Natural History) London 2 (4), 105–119.

Varma, K.K., Das, V.K., Gouveia, A.D., 1980. Thermohaline structure and watermasses in the Northern Arabian Sea during February–April. Indian Journal of Marine Science 9, 148–155.

Warren, B.A., 1981. Trans-Indian hydrographic section of lat. 18°S. Property distributions and circulation in the South Indian Ocean. Deep Sea Research 28, 759–788.